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"The Delineation and Interpretation of the Earth's Gravity Field"

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Abstract

The geoid and topographic fields of the central Pacific have been delineated and shown to correlate closely at intermediate wavelengths (500-2500 km). The associated admittance shows that anomalies having wavelengths less than about 1000 km are probably supported by the elastic strength of the lithosphere itself. Larger wavelength anomalies are due to dynamic effects in the sublithosphere. Direct modeling of small scale convection in the asthenosphere shows that the amplitudes of observed geoid and topographic anomalies can be independently matched, but that the observed admittance cannot. Only by imposing an initial regional variation in the thermal regime is it possible to match the admittance. It is proposed that this variation may be due to differences in the onset time of convection beneath lithosphere of different ages. That is, convection beneath thickening lithosphere is strongly dependent on the rate of thickening (V) relative to the rise time for convection. The critical Rayleigh number contains the length scale K/V, where K is thermal diffusivity. Young, fast growing lithosphere stabilizes the underlying asthenosphere unless it has an unusually low viscosity. Lithosphere of different age, separated by fracture zones, will go unstable at different times, producing regional horizontal temperature gradient that may strongly influence convection. Laboratory and numerical experiments are proposed to study this form of convection and its influence on the geoid.

1. Introduction

As the lithosphere moves away from a ridge it cools and thickens, forming a rigid lid over viscous mantle material. The rate of thickening decreases with time just as does the rate of heat flow through the lithosphere itself. The rigid lithosphere is a thermal and rheological boundary layer that contains most of the (negative) buoyancy associated with cooling at the surface. To establish itself, convection beneath the lithosphere uses the small, remaining part of the thermal boundary that is not contained within the rigid lithosphere. The impetus for initiation of convection thus increases with time in concert with thickening of this cool, but mobile, leading edge of the boundary layer. The time to initiate convection, the rise time, decreases with increasing accumulation of negative buoyancy; viz. rise time decreases with age of the overlying lithosphere. If the rate of growth of the lithosphere is fast compared to the rise time, incipient instability is overtaken and "frozen" into the lithosphere. The critical Rayleigh number thus involves the growth rate of the lithosphere (see later) and is only exceeded after some time when growth is sufficiently slow to allow convection. Adjoining lithosphere of different age (e.g. separated by a fracture zone) will have a different Rayleigh number and convection will be influenced by this horizontal variation in plate growth rate. The investigation of this relationship between lithosphere growth rate, onset of small scale convection, and the source of midplate geoid and gravity anomalies is the proposed subject of research.

A good deal of previous work has considered this problem of variable viscosity convection beneath a growing, highly viscous or rigid lid (e.g.

Parsons and McKenzie, 1978; Yuen et al., 1981; Yuen and Fleitout, 1984; Fleitout and Yuen, 1984; Jaupart and Parsons, 1985; Buck and Parmentier, 1986). None of these works explicitly recognize the strong stabilizing influence of a rapidly growing lithosphere. These efforts do show, however, especially that of Buck and Parmentier, that small scale convection will set in benenath the lithosphere. Most studies have assumed a quasistatic state (i.e. thickness) of the lithosphere and the overall variation of viscosity. That is, a thermal and viscous profile is assumed and then analyzed for its stability. The competition between convective risetime and lithosphere growth rate is essentially uninvestigated from an explicit analytical perspective.

We now proceed to summarize our work on this subject over the past year and in section 3 to state more clearly the proposed work for the upcoming grant period.

2. Present and Past Years Work

Over the past ten years our plan has been first to delineate the gravity and geoid fields in the Pacific, with particular emphasis on anomalies of intermediate wavelength (n,m $\simeq$ 18-22; $\lambda \simeq$ 2000 km), and then to interpret these anomalies in relation to the dynamics of the lithosphere and upper mantle (e.g. Marsh and Marsh, 1976). The method of satellite to satellite tracking (SST) was used to delineate these anomalies over the central Pacific (e.g. Marsh et al., 1981). And with the complementary data from SEASAT (e.g. Marsh et al., 1984) this anomaly set has become well established. But because some workers (e.g. Sandwell, pers. com.) feel that these anomalies could, at least in part, be artifacts of truncating spherical harmonic expansions to remove the

long wavelength (i.e. regional) effects, we have also continued research along these lines (see more below). Having established this class of anomalies, we have worked at understanding or interpreting them in terms of the isostasy of the lithosphere and convection within the underlying mantle. (Marsh and Hinojosa, 1983; Marsh et al., 1984; Hinojosa and Marsh, 1985; Hinojosa, 1986).

We have found that the most direct way to show the unequivocal existance of these anomalies is to take the full geoid (untruncated) of the central Pacific and remove a simple (first, second, or third order) surface. It is important to realize the the removed surface is not a spherical harmonic field but merely a cartesian surface, which is possible over this limited area. The resultant residual geoid is exceedingly similar to that found by removing a spherical harmonic field model ($n,m \leq 12,12$), see Figures 1 and 2. The same has been done for the bathymetry in this region, and the geoid and bathymetry has been plotted against one another (Figure 3), which gives a clear positive correlation (correl. coef. = 0.66). The slope of this correlation is also highly significant (i.e. ~ 7.5 m/km) in that it is very close to the spectrally derived admittance (see below). Altogether we are confident that this class of anomalies is real.

The understanding of these anomalies in terms of isostasy has been the subject of Hinojosa's Ph.D. dessertation (Hinojosa, 1986), the abstract of which is given as Appendix A. In brief, by treating both bathymetry and geoid in the spectral or wave number domain, the admittance has been obtained from the ratio of the geoid to the topography, which expresses the geoid anomaly in meters for every kilometer of sea-floor topography (Figure 4). The phase has also been found and it is always positive and generally small. Synthetic admittance both

for flexural and Airy compensation models have also been calculated and are shown along with the observed admittance of Figure 4. It is clear here that wavelengths shorter than about 1000 km can be compensated both regionally, by the elastic strength of the lithosphere itself, and locally by displacing mantle material to reach isostatic equilibrium. The larger wavelengths, however, cannot be explained in this fashion but must be supported dynamically within the sublithospheric mantle.

To investigate this dynamic process of compensation, Hinojosa (1986) has numerically studied the effect of convection of a variable viscosity fluid, cooled from above and heated from below on deformation of the lithosphere. Using the mean field method, with and without inclusion of a low viscosity channel, the geoid, topography, and admittance have been calculated as a function of time (see Figure 5). Although the results of this study are far too numerous to be included here, the central result is that small scale convection by itself is not strong enough to produce significant geoid and topographic anomalies that also satisfy the observed admittance. (Buck and Parmentier (1986) show that the geoid can be matched but they did not notice the problem with admittance.) But that regional thermal variations, originating, for example, at the ridge itself, carried along by the flow can cause anomalies of the observed magnitude (see Appendix A). For example, Figure 6 shows contours of geoid anomaly magnitude as a function of thermal anomaly depth and amplitude. The same has been done for topography and both results have been combined through admittance to reveal the acceptable range of thermal anomaly amplitude and depth. The critical range is 70-100°C at depths of, respectively, 100-120 km.

All of this work is now being readied for publication.

Appendix A

On the State of Isostasy in the Central Pacific:

Static and Dynamic Compensation Mechanisms

by

Juan Homero Hinojosa

A dissertation submitted to The Johns Hopkins University

in conformity with the requirements for the degree of

Doctor of Philosophy

Baltimore, Maryland

1986

Abstract

The intermediate-wavelength geoid ($\lambda \sim 2000$ km) and sea-floor topography fields in the central Pacific Ocean have been studied in terms of static and dynamic compensation models. Topographic features on the sea-floor with wavelengths shorter than about 1000 km have been found to be compensated both regionally, by the elastic strength of the lithosphere, and locally, by displacing mantle material to reach isostatic adjustment. The larger-scale sea-floor topography and the corresponding geoid anomalies with a wavelength of about 2000 km cannot be explained by either local or regional compensation. The topography and the resulting geoid anomaly at this wavelength have been modeled by considering the dynamic effects arising from viscous stresses in a layer of fluid with a highly temperature-dependent viscosity for the cases of i) surface cooling, and ii) basal heating. In this model, the mechanical properties of the elastic part of the lithosphere have been taken into account by considering an

activation energy of about 520 kJ/mol in the Arrhenius law for the viscosity. A low viscosity zone has been incorporated into the model to simulate the astenosphere. Numerical predictions of the topography, total geoid anomaly, and admittance have been obtained, and the results show that the thermal perturbation in the layer, which accounts for the mass deficit, must be located close to the surface to compensate the gravitational effect of the surface deformation. For the case of basal heating, both hot and cold thermal boundary layers develop. In the low viscosity regions, convective motions are vigorous. In the colder regions, however, the viscosity is high, and the motions nearly vanish. This response to cooling results in the separation of the upper, quasi-rigid lid from the lower mobile fluid, hence inhibiting the development of a compensating thermal perturbation at shallow depths. The geophysical observables can be well explained by a shallow, transient thermal perturbation, most likely originating at the East Pacific Rise and being brought close to the surface by the large-scale mantle flow.

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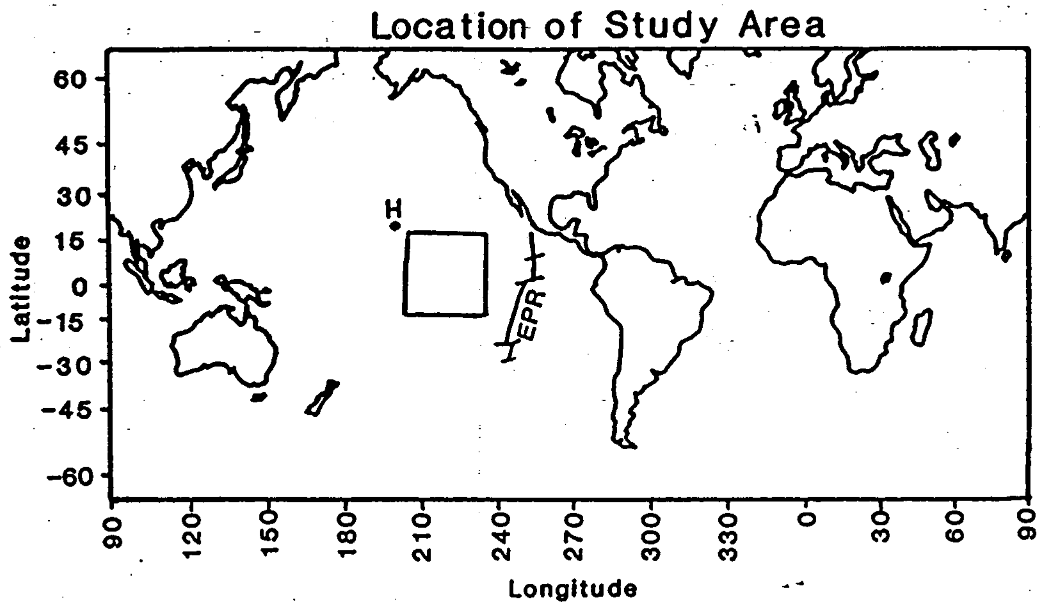

Figure 1. Map showing the location of the study area in the central Pacific Ocean.

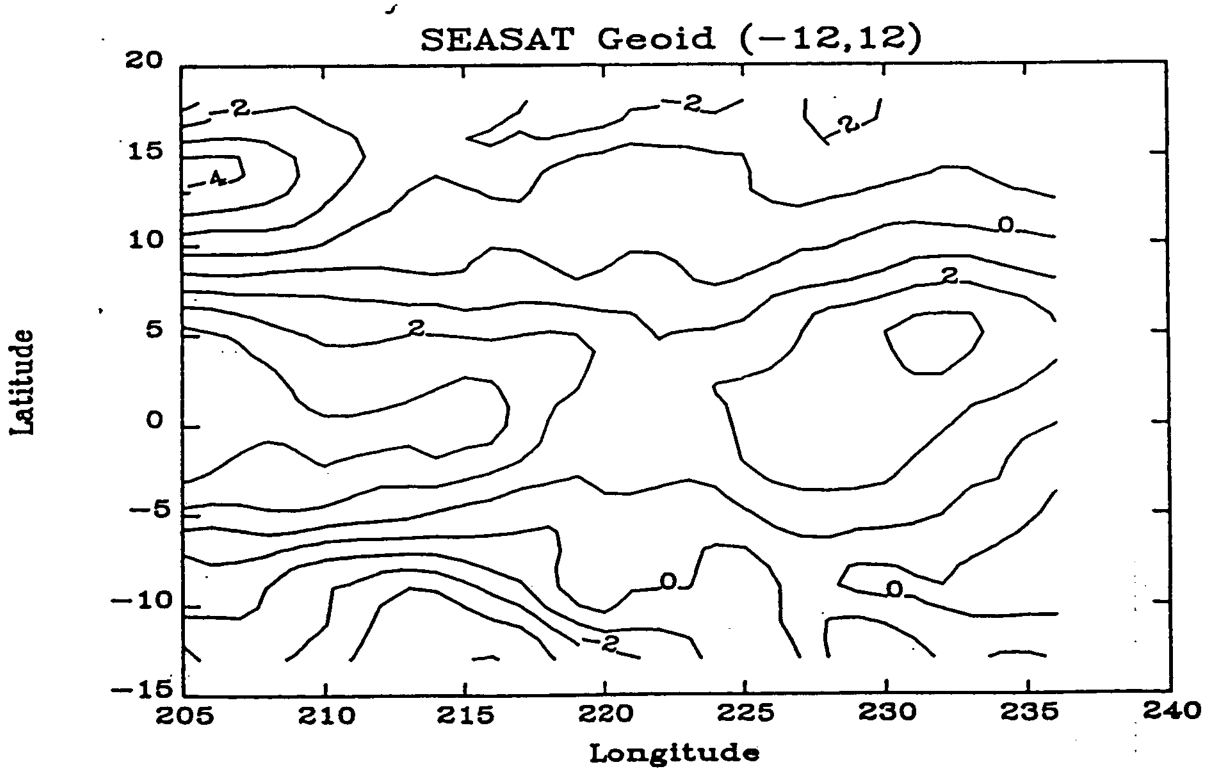

Figure 2a. Contour map showing the high degree and order SEASAT geoid (-12,12) in the study area. Contour interval = 1 m.

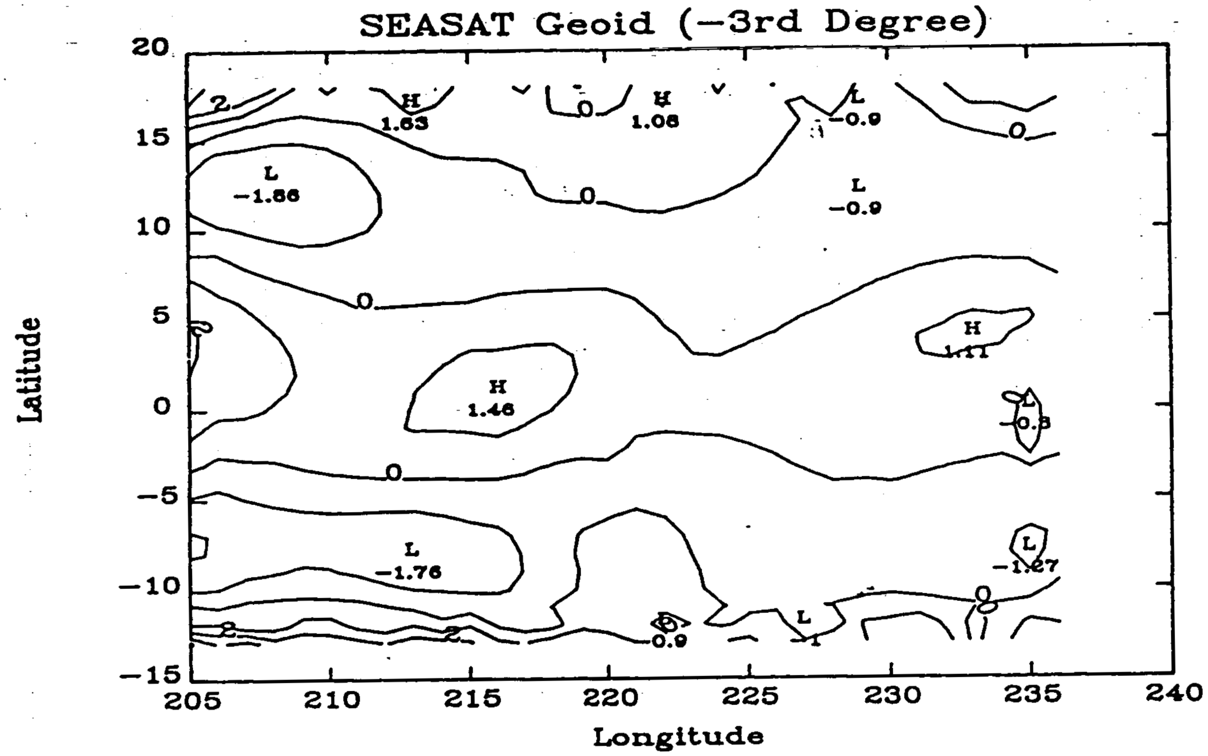

Figure 2b. The resultant geoid field after removing a third degree surface from the full geoid in Figure 2a. Contour interval = 1 m.

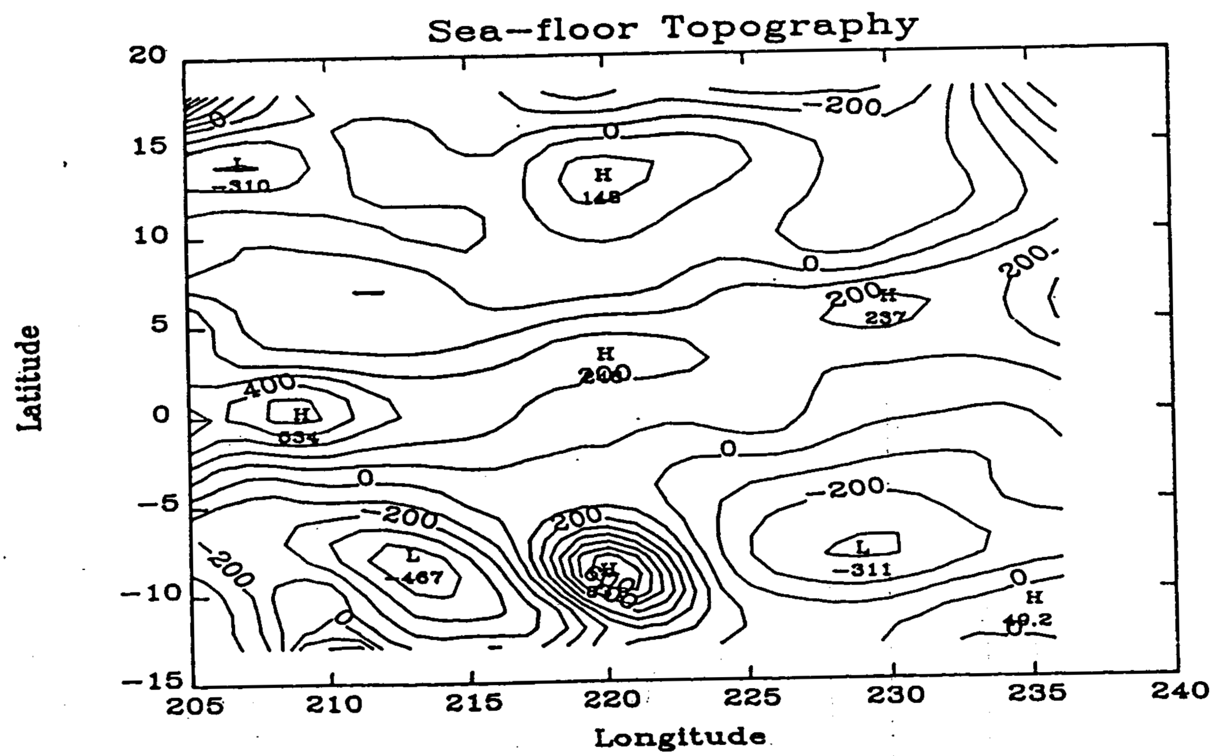

Figure 2c. Contour map showing the sea-floor topography obtained by Gaussian high-pass filtering the bathymetry in the study area.
Contour interval = 100 m.

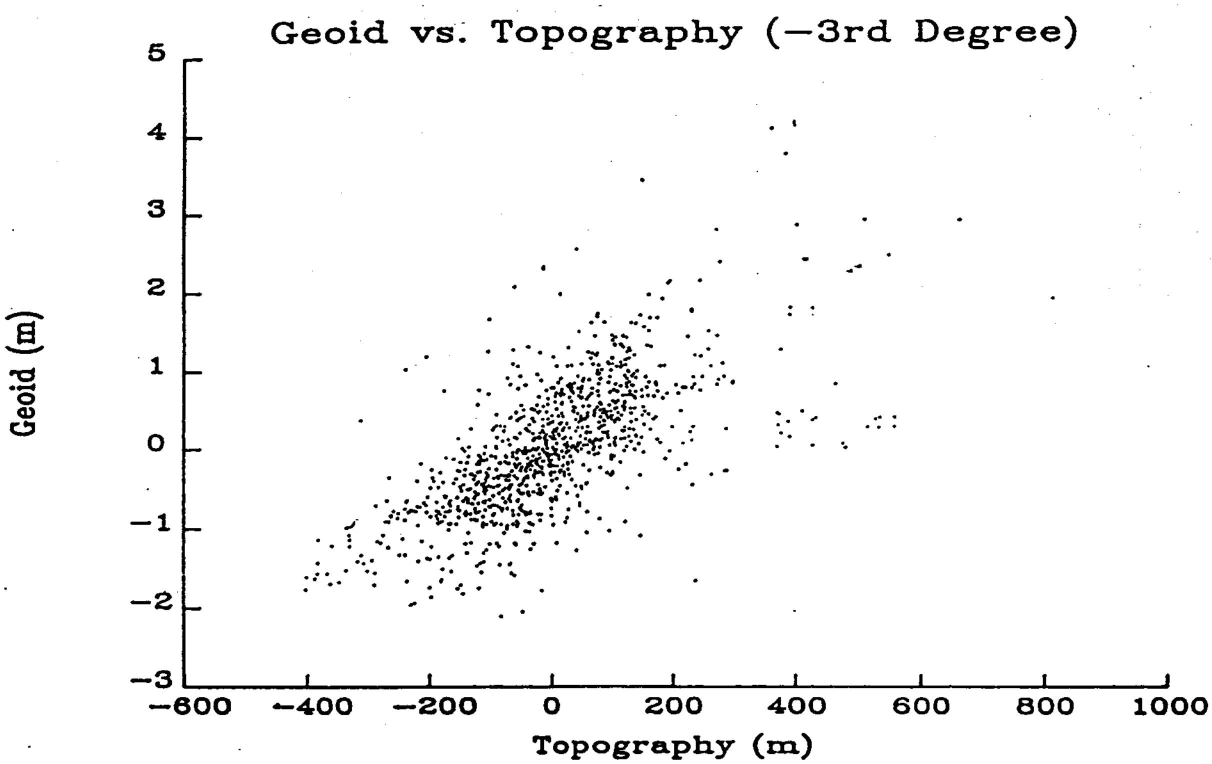

Figure 3 . Scatter plot of the geoid (Fig.2b) and topography (Fig.2c).

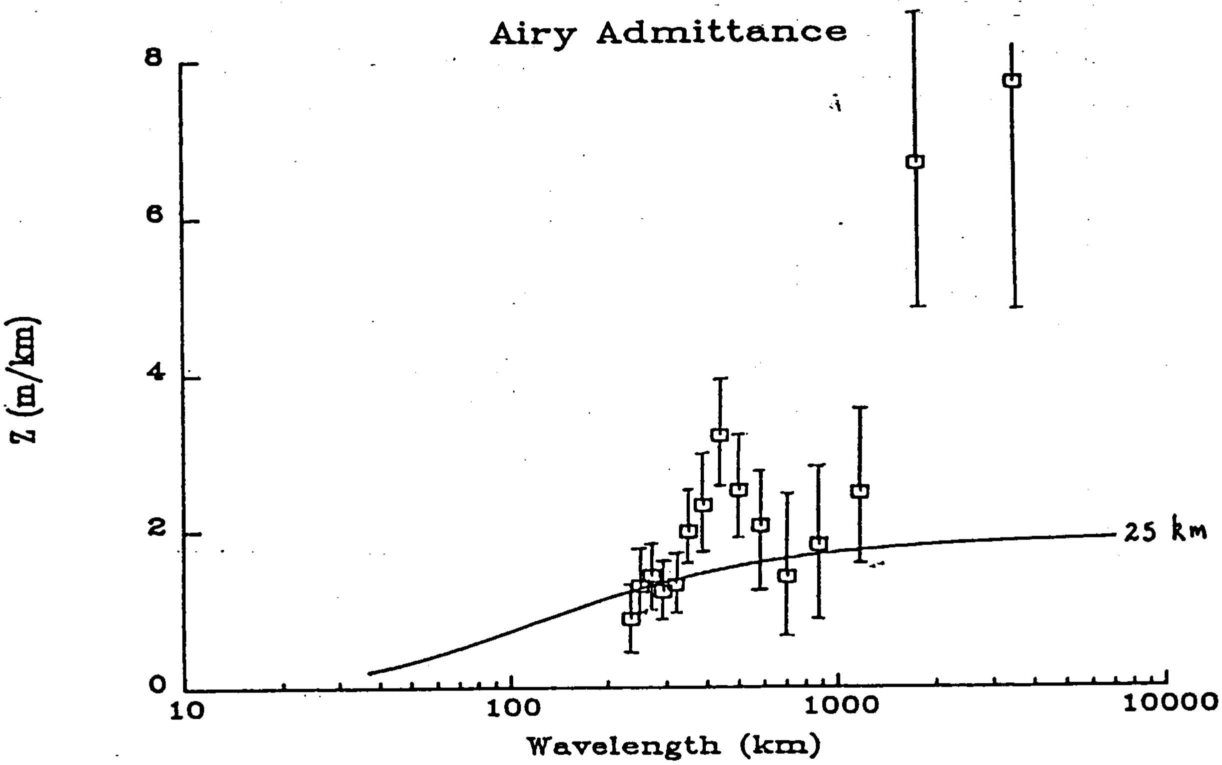

Figure 4a. Comparison of the observed admittance spectrum with the Airy model admittance curve corresponding to a depth of compensation of 25 km.

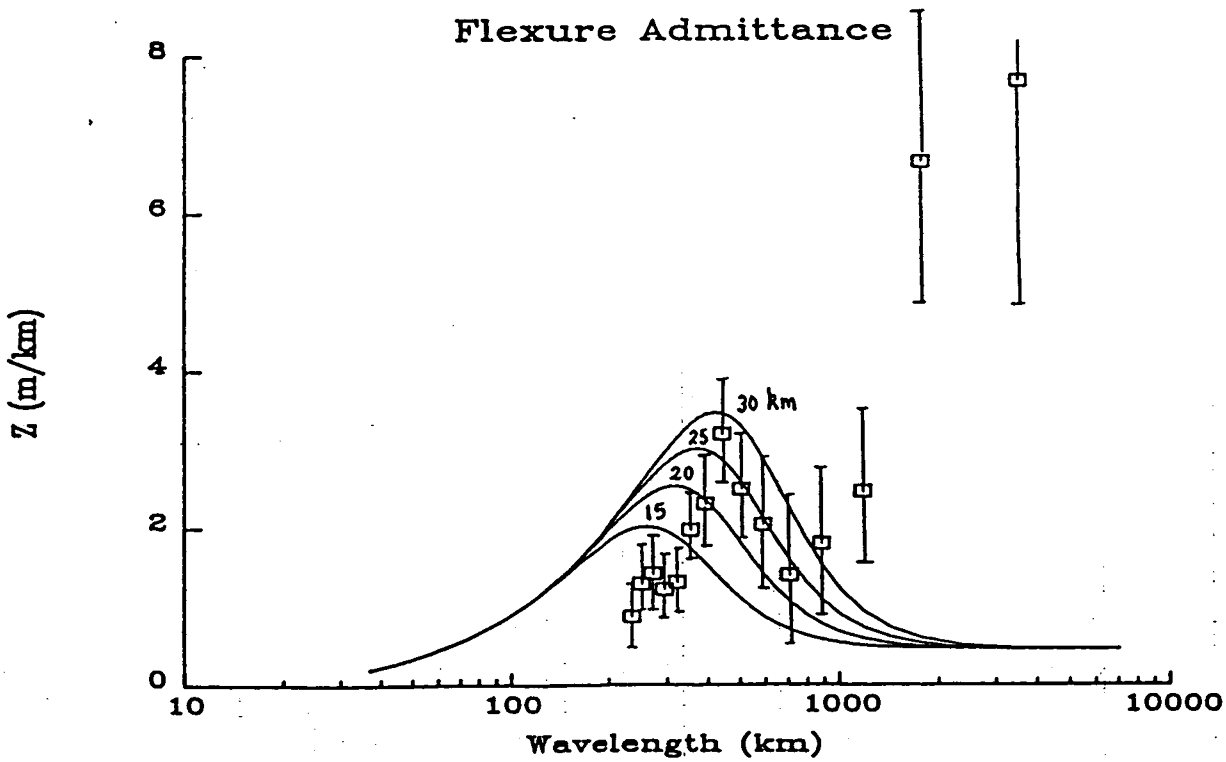

Figure 4b. Comparison of the observed admittance spectrum with flexure model admittance curves for the values of the elastic plate thicknesses shown next to each curve.

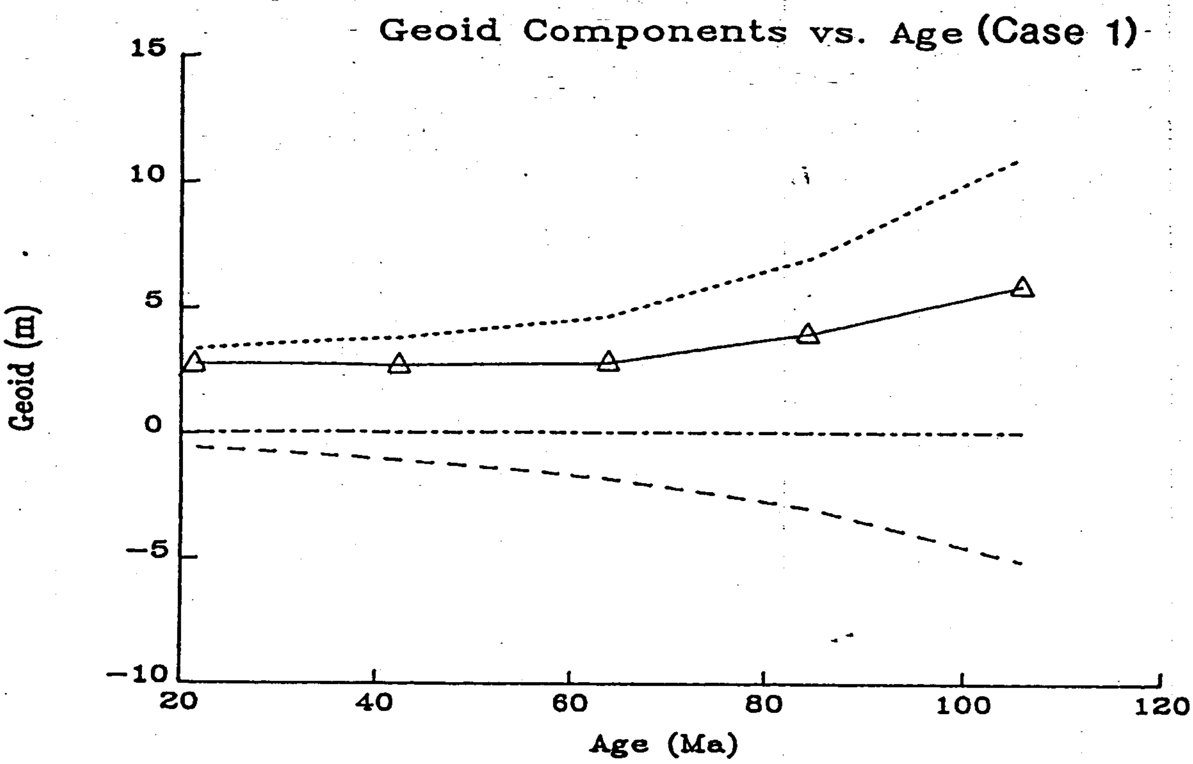

Figure 5a. The geoid components as a function of age for case 1.
The open triangles are the calculated values. The solid line is the total geoid anomaly, the dotted line is the upper-boundary-deformation contribution, the dashed line is the thermal contribution, and the dot-dashed line is the lower-boundary-deformation contribution.

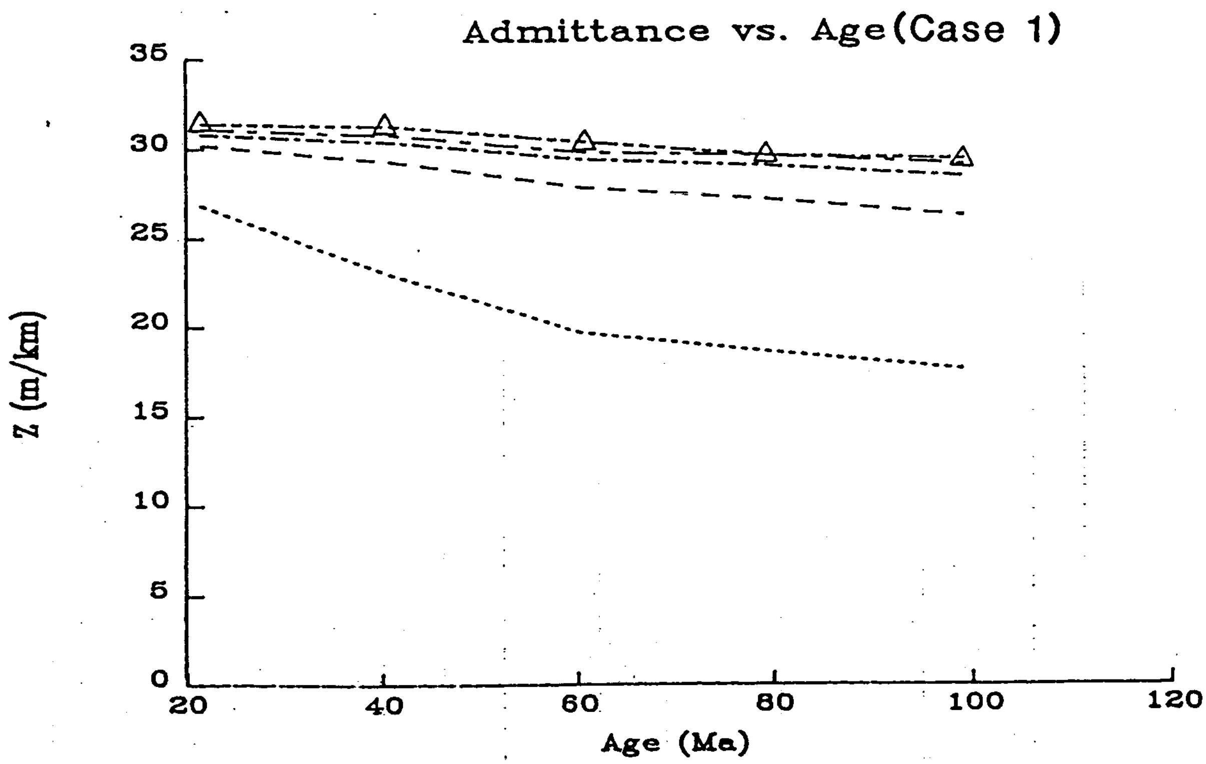

Figure 5b. The admittance as a function of age for case 1 with the different values for the activation energy.

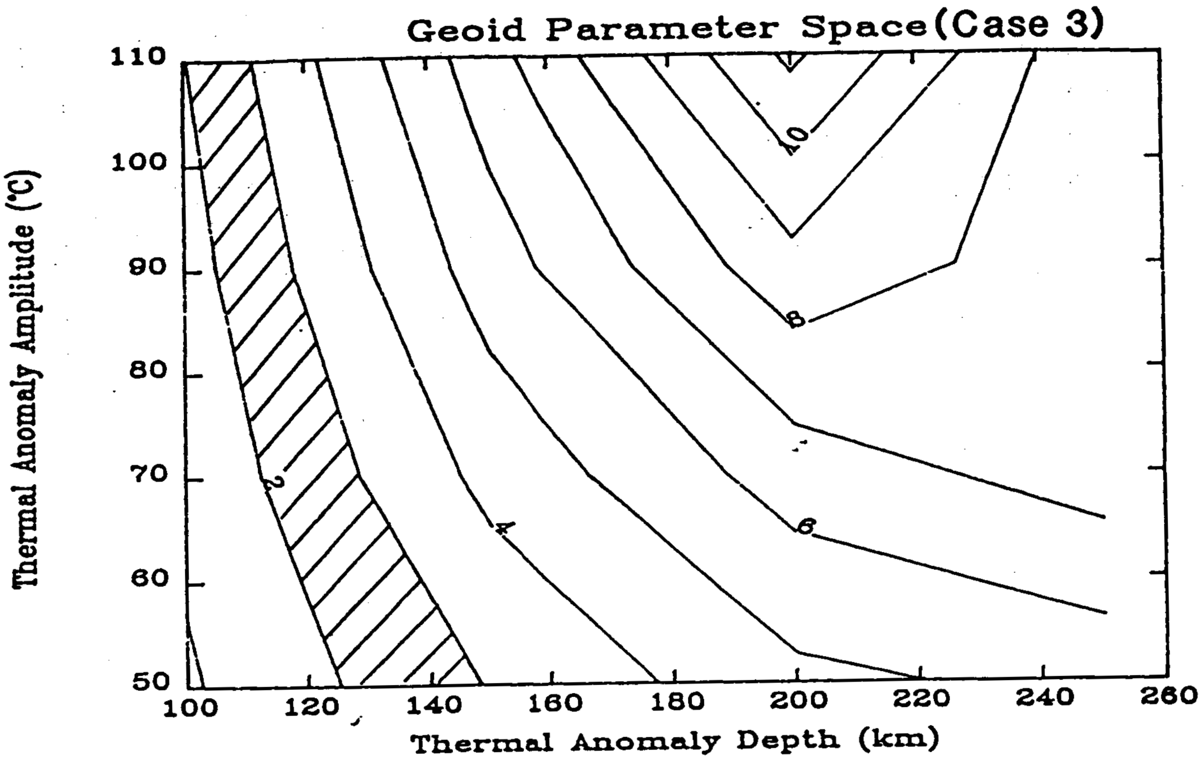

Figure 6 . The parameter space for the predicted geoid anomaly for case 3 in which the fluid layer is cooled from above, the lower boundary temperature is fixed at 1300° C, the Rayleigh number is 585 000, the mean viscosity at T = 1300° C is 1.E22 Poise, the activation energy is 526 kJ/mol, the cut-off temperature is 950° C, and the initial LVZ temperature is 1350° C extending to a depth of 200 km. The thermal perturbation was initially introduced extending from the surface down to a given depth (horizontal axis) and of a given initial amplitude (vertical axis). The values correspond to an age of about 60 Ma. The hatched area corresponds to the range of the observed geoid anomaly. Contour interval = 1 m.